Exercise profile and effect on growth traits, carcass yield, meat quality, and tibial strength in Chinese Wannan chickens

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ABSTRACT The aim of the study was to understand the dynamic changes in daily step counts (**DSC**) during the development of chickens and to further explore the effects of exercise on the growth performance, carcass yield, meat quality, and tibial strength of cocks. A total of 600 (half male and half female) 1-day-old Wannan chickens with similar hatching weights were raised under the same rearing conditions. All birds were wing banded and housed in identical cages for from 1 to 8 wk in the experimental poultry house. The dimensions of the cages were 70 × 70 × 40 cm (length × width × height). At the age of 9 to 16 wk, these birds were reared in indoor pens (2 m × 2 m, 1,000 cm^2 per bird). In addition, they also had a free-range grass paddock (20 m × 30 m, 1 m^2 per bird). The DSC of male and female Wannan chicks were recorded from 70 to 112 d by using a pedometer. At 112 d of age, based on the average DSC, birds were divided into groups representing the highest (**HS**), medium, and lowest (**LS**) number of step groups. Fifteen cocks from each group were selected for subsequent experiments. Compared with the LS group, the HS group displayed higher tibial strength ($P = 0.025$) and lower BW, cooking loss ($P = 0.014$), shear force ($P = 0.023$), and drip loss ($P = 0.008$). The DSC had no effects on the female BW or male carcass parameters. There was no significant change in the DSC of all birds from 70 to 112 d. However, male chickens took more steps than females at 15 ($P = 0.025$) and 16 ($P = 0.012$) week of age. In conclusion, the effects of the DSC on the BW of Wannan chickens depend on sex, and enhanced exercise could improve the meat quality and tibial strength of cocks.

Key words: chicken, daily step count, growth trait, carcass yield, meat quality

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INTRODUCTION

Exercise was reported to be one of the important factors that could affect the production, egg quality, and well-being of chickens (Abrahamsson and Tauson, 1995; Fleming et al., 2006; Mattioli et al., 2017). Reduced exercise may result in physical and psychological distress, which has a considerable effect on the quality and quantity of animal products (Noble et al., 1996; Mattioli et al., 2017). However, in modern poultry industry, chickens are confined at high density and are almost totally physically inactive (Lei and van Beek, 1997; Bizeray et al., 2002a,b). Recently, many studies have attempted to provide environmental enrichment to modify chicken activity. Examples of types of environmental enrichment include adding ramps or barriers between water and food (Ruiz-Feria et al., 2014), providing perches (Ventura et al., 2010), and changing the rearing system (Semwogerere et al., 2018) and lighting programs (Wei et al., 2020). Changes in these environmental factors were reported to affect growth. Lei and van Beek (1997) concluded that activity driven by using vertical fans can increase broiler BW. However, Li et al. (2017) reported that increased bird physical activity by rearing in a free-range raising system has negative effects on growth performance. Moreover, Bizeray et al. (2002a) and Wang et al. (2009) reported that there was no relationship between physical activity and production performance. Modification of environmental factors to affect physical activity may also have considerable effects on carcass composition and meat quality of chickens, but the results are variable (Lei and van Beek, 1997; Wang et al., 2009; Guo et al., 2019). Physical activity is a complicated trait and has proven to be difficult to quantify, which may be the main reason for the aforementioned debate.

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Previously, we used a pedometer to record and quantify the amount of exercise in chickens by counting daily steps (Guo et al., 2019). We found that increased exercise improved BW and meat quality but had no effect on other carcass traits. However, our previous study provides only a static picture of the dynamic process associated with daily step counts (**DSC**) during chicken development. Moreover, the effects of exercise (DSC) on production performance, meat quality, and tibial strength of cocks remain enigmatic. In addition, the difference in DSC between males and females was also unclear.

In the present study, pedometers (Supplementary Figure 1) were used to record and quantify the walking steps of Wannan chickens to study dynamic changes in DSC during the development of chickens and further explore the effects of exercise on growth performance, carcass yield, meat quality, and tibial strength of cocks.

MATERIALS AND METHODS

Birds and Housing

All bird handling protocols were approved by the Animal Care and Use Committee of Anhui Agricultural University (Hefei, China).

A total of 600 (half male and half female) 1-day-old Wannan chickens (a dual-purpose breed from China) with similar hatching weights were raised under the same rearing conditions. All birds were wing banded and housed in identical cages for from 1 to 8 wk in the experimental poultry house. The dimensions of the cages were 70 × 70 × 40 cm (length × width × height). One cage was equipped with 2 nipples and 1 feeding trough in front of the cage. The stocking density was identical for all birds (122.5 cm^2 per bird, 1 to 2 wk; 245 cm^2 per bird, 3 to 6 wk; 490 cm^2 per bird, 7 to 8 wk). At the age of 9 to 16 wk, these birds were reared in indoor pens (2 m × 2 m, 1,000 cm^2 per bird). One 5-kg feeder and one plasson water fountain were located inside each pen. The litter height in each indoor floor pen was approximately 5 cm. In addition, they also had a free-range grass paddock (20 m × 30 m, 1 m^2 per bird). The temperature was initially maintained at 32 to 34°C at 1 wk of age and then lowered by 2°C per week until the ambient temperature was approximately 20°C. The birds were given 23 h of light per day at week 1. During week 2, the daytime length was reduced to 20 h and to 18 h for week 3, 16 h for week 4, and 12 h at week 5, wherein it remained through week 16. Birds had ad libitum access to water and a pellet diet appropriate for the stage of development (1–3 wk: CP, 20.5% and ME, 12.59 MJ/kg; 4 to 7 wk: CP, 18.5% and ME, 12.98 MJ/kg; and 8 to 16 wk: CP, 17.0% and ME, 11.75 MJ/kg). Mortality was recorded when it occurred.

Daily Step Counts

Daily step counts were recorded for all birds between 70 and 112 d of age using a pedometer (Shanghai QST Corporation, Shanghai, China), and the average steps per day are presented in Supplementary Figure 2. At 112 d of age, 20 male birds and 20 female birds (including unhealthy birds and those that had experienced mortality) were excluded from the analysis, and the remaining 280 male birds and 280 female bird records were available for quality control of the DSC. Then, based on the average DSC, 280 male birds and 280 female birds, respectively, were ranked and divided into groups with the highest (**HS**), medium (**MS**), and lowest (**LS**) step counts (Supplementary Table 1). Then, from each group, 15 male birds whose step counts were close to the average were selected for growth trait, carcass composition, meat quality, and tibial strength analyses.

Growth Performance, Comb Size, and Body Size

The BW of all birds was measured at 0, 4, 7, 10, 13, and 16 wk of age; comb size and body size of each male bird were measured at 16 wk of age. Comb length (maximum length of comb) and height (from the top of the comb to the head) were measured as per the study by Chen et al. (2010). Body slope length (from the shoulder joint to ischial tuberosity), chest width (between 2 shoulder joints), chest depth (from the first thoracic vertebra to keel), keel length (from the front end of the keel to the end of the keel), and tibia circumference (circumference of the middle shank) were measured as per the study by Tyasi et al. (2017). Tibia length and the distance from the hind corner of the hock joint to the first scale of the third (middle) toe were measured using a vernier caliper (Gao et al., 2009).

Carcass Traits and Meat Quality

At day 112, individual chicken BW and body measurements were recorded after a 12-hour fast. Then, from each group, 15 male birds whose step counts were close to the average were selected for euthanasia by electrical stunning followed by exsanguination. Then, the birds were defeathered and weighed. The dressing percentage was calculated as the ratio between carcass weight and BW. The partially eviscerated weight (**PEW**) was measured for carcasses with nonedible viscera (intestines, proventriculus, gall bladder, spleen, esophagus, and full crop) removed. The full eviscerated weight was measured from the PEW after removal of edible viscera (heart, liver, and gizzard), head, neck, legs, and fat (perivisceral, perineal, and abdominal). Then, the proportion of the PEW and full eviscerated weight in the live BW was calculated. After the birds were manually eviscerated, the heart, liver, lung, spleen, breast muscle (including pectoralis major and pectoralis minor), and leg muscle (including thigh and drumstick) were all analyzed. The proportions of the heart, liver, lung, spleen, breast muscle, and leg muscle were calculated as a percentage of the respective live weights of the birds.

Table 1. Comparison of average steps per day among male and female birds.

Age (week)	Average male steps per day	Average female steps per day	*P*-value
11	20,452.63 ± 2,366.73	18,501.01 ± 2,370.77	0.135
12	20,168.87 ± 2,606.23	17,776.96 ± 2,424.44	0.114
13	20,269.92 ± 2,613.00	17,771.11 ± 2,618.73	0.093
14	18,817.11 ± 2,356.91	16,821.11 ± 2,344.36	0.075
15	21,540.66 ± 3,029.65	18,823.46 ± 2,429.65	0.025
16	21,527.13 ± 3,113.20	18,603.89 ± 2,376.25	0.012

Values are expressed as mean ± SD (n = 280).

Pectoralis major muscles were collected from the left side of the breast muscle and stored at 4°C for pH, meat color, cooking loss, and shear force analyses. Meanwhile, pectoralis major muscles were collected from the right side of the breast muscle, and then, some of the samples were used to determine drip loss; others were stored at −20°C for intramuscular fat analysis. For drip loss analysis, the sample was cut into strips (1 × 2 × 0.5 cm) parallel to the longitudinal orientation of the muscle fiber and then put in a sealed pocket at 4°C for 24 h; the percentage of weight loss during storage was calculated. The pH at 24 h was measured in triplicate using a PHB-4 pH meter (INESA Scientific Instrument Co., Ltd., Shanghai, China). Meat color (L*, a*, and b* values) at 24 h postmortem was measured in triplicate using a Tristimulus colorimeter (CR-410; Konica Minolta (China) Investment Ltd., Shanghai, China), which was previously calibrated against a white tile according to the manufacturer's instructions. For cooking loss measurement, the aforementioned muscle samples for meat color measurement were heated in plastic bags in a water bath at 85°C for 20 min. Cooking loss values were calculated as the percentage of weight loss during cooking. The aforementioned cooked muscle samples were manually trimmed into rectangular shapes with a size of 1.0 cm (width) × 1.0 cm (thickness) × 3.5 cm (length) parallel to the longitudinal orientation of the fiber, and then, shear force values were measured in triplicate using a digital texture analyzer (C-LM3; Northeast Agricultural University, Harbin, China). For intramuscular fat measurement, pectoralis major muscle samples were dried at 65°C and subsequently pulverized, and then, the samples were examined via the Soxhlet method using diethyl ether as the extraction solvent (AOAC, 1995).

Tibial Strength

After euthanasia, left tibia samples were wrapped in saline-soaked gauze and stored at −20°C for tibial strength analyses. During testing, bones were thawed at room temperature and kept wet using 0.9% wt/vol saline solution. Then, the experiments were conducted on an Instron 3367 Universal Test Machine (Model #4204; Instron Corp., Canton, MA). The machine had a 30-kN load capacity and 2 platforms, which were controlled to fracture the bone between the platforms. The test was set up so that the top platform moved vertically downward toward the midpoint of the bone shaft at a rate of 10 mm/min, with a 15% load rate. The machine was stopped upon the distinct rapid decline in force and simultaneous sound of bone fracturing. The results are presented as newtons of force required to break each bone.

Statistical Analyses

The statistical analysis of the data was performed using SPSS 19.0 for Windows statistical software package (SPSS Inc., Chicago, IL). The data of average steps per day among male and female birds were analyzed using a simple *t* test. All other data were analyzed using a one-way ANOVA model, followed by Duncan's multiple range analysis, with each bird as the experimental unit. The threshold for significance was set at $P < 0.05$. Data are expressed as mean ± SD.

RESULTS

Daily Step Count

The average steps per day are presented in Supplementary Figure 2. The average number of daily

Table 2. Comparison of male BW among the HS, MS, and LS groups at different ages.

Age (week)	HS (n = 93)	MS (n = 94)	LS (n = 93)	*P*-value
0	29.98 ± 4.32	31.13 ± 2.74	31.06 ± 3.50	0.102
4	233.00 ± 28.49^{b}	238.88 ± 24.19^{a,b}	249.90 ± 23.30^{a}	0.045
7	495.67 ± 41.68^{b}	513.60 ± 40.83^{a,b}	531.46 ± 23.35^{a}	0.034
10	832.02 ± 47.95^{b}	863.92 ± 71.02^{a,b}	898.67 ± 72.93^{a}	0.023
13	1,181.35 ± 89.70^{b}	1,223.35 ± 106.00^{b}	1,284.25 ± 120.86^{a}	0.009
16	1,418.91 ± 109.54^{b}	1,442.09 ± 134.03^{b}	1,521.05 ± 130.84^{a}	0.008

^{a,b}Means in the same row with no common superscript differ significantly ($P < 0.05$). Values are expressed as mean ± SD.

Abbreviations: HS, highest number of steps; LS, lowest number of steps; MS, medium number of steps.

Table 3. Comparison of female BW among the HS, MS, and LS groups at different ages.

Age (week)	HS (n = 93)	MS (n = 94)	LS (n = 93)	*P*-value
0	31.06 ± 2.59	31.14 ± 3.48	31.05 ± 2.93	0.351
4	209.97 ± 18.96	209.08 ± 20.50	211.56 ± 20.31	0.243
7	437.89 ± 51.35	435.90 ± 46.05	451.41 ± 55.32	0.097
10	681.68 ± 63.84	680.29 ± 74.46	687.65 ± 69.42	0.342
13	940.17 ± 92.28	952.12 ± 92.03	970.63 ± 106.30	0.112
16	1,115.24 ± 97.37	1,124.50 ± 111.00	1,144.20 ± 96.15	0.543

Values are expressed as mean ± SD.
Abbreviations: HS, highest number of steps; LS, lowest number of steps; MS, medium number of steps.

steps at 12 and 13 wk was relatively stable and remained more than 19,000 steps, but the average number of daily steps at 11 wk to 14 wk showed an overall downward trend. At 15 and 16 wk, the value increased to more than 20,000 steps.

Comparison of DSC Among Males and Females

As shown in Table 1, although there was no significant difference in the average number of daily steps at 11 to 14 wk of age, the males always took more steps than the females ($P > 0.05$). Compared with the female birds, the male birds displayed a higher average number of daily steps at 15 ($P = 0.025$) and 16 wk of age ($P = 0.012$).

Growth Performance

BW values are presented in Table 2 and Table 3. The male BW of the LS group was higher than that of the HS group at 4 to 16 wk of age ($P < 0.05$). Compared with the MS group, the LS group displayed higher BW at 13 ($P = 0.009$) and 16 ($P = 0.008$) week of age. There were no significant differences in female BW among the 3 groups from 0 to 16 wk of age.

Comb Size and Body Size

The effects of exercise on males' comb and body measurements at 16 wk of age are presented in Table 4. Comb height was not significantly affected by exercise ($P = 0.165$). However, birds in the HS group presented longer combs ($P = 0.007$) than those in the MS and LS groups. Birds in the HS group exhibited shorter tibia lengths ($P = 0.035$) and lower tibia circumferences ($P = 0.035$) than birds in the MS and LS groups. There were no significant differences in other body sizes among the 3 groups ($P > 0.05$).

Carcass Characteristics

Carcass parameters of males are presented in Table 5. The percentage of heart weight was greater in the HS group than in the MS and LS groups ($P = 0.032$). There were no significant differences in other carcass characteristics among the 3 groups ($P > 0.05$).

Meat Quality

As shown in Table 6, the LS group displayed higher cooking loss ($P = 0.014$), shear force ($P = 0.023$), and drip loss ($P = 0.008$) than the HS group. There were no significant differences in other meat quality parameters among the 3 groups ($P > 0.05$).

Strength of the Tibia

The strengths of the male tibias at 16 wk of age are presented in Figure 1. Compared with the LS group, the HS group displayed a higher tibial strength ($P = 0.025$).

Table 4. Effect of exercise on males' comb and body measurements at 16 wk of age.

Item	HS (n = 93)	MS (n = 94)	LS (n = 93)	*P*-value
Comb length (mm)	60.26 ± 4.94[a]	55.63 ± 4.78[b]	55.86 ± 5.89[b]	0.007
Comb height (mm)	27.57 ± 2.56	26.32 ± 2.94	26.02 ± 2.66	0.165
Chest width (mm)	42.69 ± 4.98	41.48 ± 3.22	42.3 ± 4.50	0.234
Chest depth (mm)	92.74 ± 6.67	93.41 ± 4.57	95.28 ± 5.65	0.067
Keel length (mm)	116.03 ± 5.51	117.93 ± 6.01	117.33 ± 6.68	0.089
Tibia length (mm)	109.65 ± 4.01[b]	112.29 ± 4.93[a]	112.20 ± 3.80[a]	0.035
Tibia circumference (mm)	39.12 ± 1.39[b]	40.18 ± 1.44[a]	40.08 ± 1.35[a]	0.026
Body slope length (mm)	224.10 ± 7.82	222.21 ± 8.83	224.93 ± 7.29	0.647

[a,b]Means in the same row with no common superscript differ significantly ($P < 0.05$). Values are expressed as mean ± SD.
Abbreviations: HS, highest number of steps; LS, lowest number of steps; MS, medium number of steps.

Table 5. Comparison of males' carcass traits among the HS, MS, and LS groups.

Item	HS	MS	LS	*P*-value
Dressing percentage (%)	90.03 ± 1.12	90.01 ± 1.17	90.10 ± 1.97	0.336
Partially eviscerated carcass (%)	78.35 ± 1.71	78.54 ± 1.62	78.94 ± 1.41	0.746
Full eviscerated weight (%)	64.64 ± 1.36	64.64 ± 1.34	65.18 ± 1.69	0.139
Percentage of heart weight (%)	0.93 ± 0.09[a]	0.77 ± 0.09[b]	0.80 ± 0.11[b]	0.032
Breast muscle yield (%)	16.83 ± 1.33	17.68 ± 1.64	18.84 ± 0.79	0.319
Leg muscle yield (%)	23.03 ± 1.33	22.52 ± 0.90	23.25 ± 1.70	0.194
Percentage of liver weight (%)	3.48 ± 0.41	3.72 ± 0.46	3.69 ± 0.42	0.087
Percentage of lung weight (%)	1.11 ± 0.18	1.19 ± 0.18	1.10 ± 0.14	0.079
Percentage of spleen weight (%)	0.32 ± 0.04	0.31 ± 0.04	0.30 ± 0.04	0.094

[a,b]Means in the same row with no common superscript differ significantly ($P < 0.05$). Values are expressed as mean ± SD (n = 15).

Abbreviations: HS, highest number of steps; LS, lowest number of steps; MS, medium number of steps.

DISCUSSION

Our results showed that the average DSC of all birds decreased from week 11 to week 12. This pattern may be attributed to the birds adapting to being equipped with the pedometer. At 14 wk of age, the average DSC decreased drastically, which may have resulted from continuous rain. The average number of walking steps did not significantly differ between 15 and 16 wk when compared with 12 and 13 wk. Moreover, the males took more steps than the females at 15 and 16 wk of age. These results indicated that sex and environmental factors, but not age, could affect the amount of exercise during the adolescent stage of Wannan chickens.

Increased exercise had no effects on female bird BW, a result that was consistent with that of Bizeray et al. (2002a), who reported that adding barriers between feed and water had no effect on BW. However, increased exercise decreased the BW of male birds. Similar results have been reported previously. For example, Li et al. (2017) demonstrated that the growth performance of birds in the free-range raising system was inferior to that of birds raised in more controlled environments because the free-range birds were exposed to fluctuating temperatures and increased exercise in the yards, thus increasing their energy requirement and influencing their feed conversion. However, our team's previous study, by Guo et al. (2019), reported that increased exercise improved BW, and Noble et al. (1996) also reported that increased physical activity accomplished by changing feed and water locations could enhance the weight of turkeys. The reasons for these discrepancies could be attributed to differences in breed and sex and increased exercise leading to more energy consumption for activity and less energy consumption for body growth. It is well known that male birds grow faster than female birds in many species of poultry. Liu et al. (2011) showed that male Yangzhou geese exhibited higher BW, BW gains, and feed conversion ratios than female geese. Consistent with this, we found that male Wannan chickens grew faster than female Wannan chickens in the present study.

The comb, as a secondary sexual characteristic, is an important trait in chickens. Most studies have reported that comb size is associated with sexual maturity (Mukhtar and Khan, 2012). In addition, the comb has been reported to affect male social rank, mate choice, heat regulation, and sperm quality (van Kampen, 1971; Udeh et al., 2011) and is related to female egg production, fecundity, and bone mass (Pizzari and Snook, 2003; Cornwallis and Birkhead, 2007). The present study showed that birds in the HS group presented longer combs than those in the MS and LS groups ($P < 0.05$). The results suggest that increased exercise may have a positive effect on male comb size. Therefore, in practice, it can be considered to increase exercise in adolescent cocks.

We found that increased exercise results in reduced tibial length and circumference. This is partly in contrast to the finding of Bizeray et al. (2002b), who reported that birds maintained with barriers had wider tibias than control birds. We could not provide a scientific

Table 6. Comparison of meat quality traits among the HS, MS, and LS groups.

Item	HS	MS	LS	*P*-value
Cooking loss (%)	24.84 ± 1.01[b]	25.46 ± 1.57[a,b]	26.70 ± 1.20[a]	0.014
Shear force (N)	29.10 ± 3.53[b]	29.50 ± 2.42[a,b]	31.18 ± 2.78[a]	0.023
Drip loss (%)	1.03 ± 0.08[b]	1.11 ± 0.13[b]	1.28 ± 0.11[a]	0.008
Intramuscular fat (%)	1.80 ± 0.37	1.89 ± 0.26	1.89 ± 0.37	0.245
L*	54.19 ± 3.55	55.84 ± 5.36	54.07 ± 3.47	0.167
a*	10.43 ± 1.08	9.93 ± 0.96	10.06 ± 1.00	0.435
b*	19.82 ± 2.77	21.67 ± 3.02	18.65 ± 2.56	0.064
pH_{24h}	6.09 ± 0.17	6.13 ± 0.17	6.06 ± 0.15	0.443

[a,b]Means in the same row with no common superscript differ significantly ($P < 0.05$). Values are expressed as mean ± SD (n = 15).

Abbreviations: a*, redness; b*, yellowness; HS, highest number of steps; L*, lightness; LS, lowest number of steps; MS, medium number of steps.

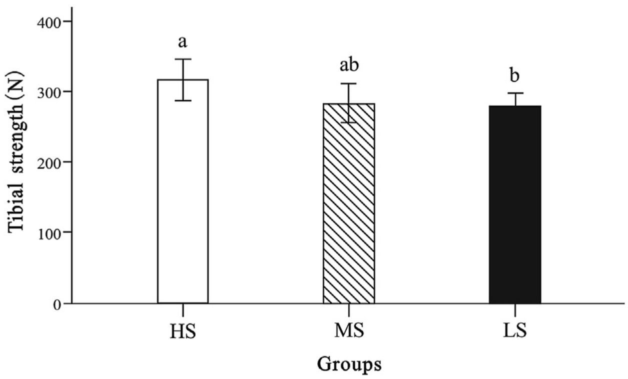

Figure 1. Comparison of tibial strength among the HS, MS, and LS groups. Each bar presents mean ± SD (n = 15). Within a panel, bars labeled with different letters significantly differ ($P < 0.05$). Abbreviations: HS, highest number of steps; LS, lowest number of steps; MS, medium number of steps.

explanation for birds with a high number of step counts having shorter tibial lengths and circumferences, which needs to be investigated in future studies. We further explored the differences in tibial strength and found that the HS group displayed a higher tibial strength than the LS group. This result is consistent with that of Casey-Trott et al. (2017), who reported that chickens reared in an aviary rearing system displayed greater bone breaking strength, bone density, and total bone mineral content than chickens from conventional cages, which indicates that exercise could enhance the bone characteristics of chickens.

Increased exercise improved heart weight, and similar findings have been reported by Oscai et al. (1971), who demonstrated that animal exercise actuated by swimmers significantly increased heart weight-to-BW ratios compared with that of sedentary paired-weight animals. However, it had no effects on other carcass yield metrics, which is in agreement with the results of Wang et al. (2009), who reported that a free-range raising system had no effect on the eviscerated carcass or breast, thigh, and wing yield in a slow-growing chicken breed. Meanwhile, Castellini et al. (2002) and Feddes et al. (2002) stated that the eviscerated carcass percentage significantly increased when birds had outdoor access because of increased motor activity. In this study, birds from the HS group exhibited lower BW than birds from the LS group but had a greater heart ratio and no differences in other carcass metrics compared with the LS group. This indicated that chickens in the HS group may have lower abdominal fat than those in the LS group because the increased motion reduced abdominal fat content, consistent with the results of Lei and van Beek (1997). Unfortunately, abdominal fat was not measured in the present study and would need to be investigated in future studies.

In recent years, consumers demand for higher quality chicken meat has increased, especially in China (Zhang et al., 2017). Both the water-holding capacity (**WHC**) and shear force are important quality attributes. The WHC refers to the ability of meat to retain water during slaughter, storage, processing, and transportation. The WHC is often described by the loss of water droplets. Lower WHC indicate nutrient loss through released exudates, resulting in drier and tougher meat. Shear force represents the ease with which the muscle is chewed or cut and is one of the most important sensory characteristics of meat. The present study showed that chickens from the HS group displayed lower cooking loss, shear force, and drip loss than those from the LS group, which is consistent with the results of Guo et al. (2019). These results suggested that exercise could contribute to the juiciness and tenderness of chicken meat.

In conclusion, sex could affect the amount of exercise needed during the adolescent stage. Increased exercise could improve bone characteristics but had negative effects on male BW and had no effects on carcass composition. Exercise could contribute to the juiciness and tenderness of meat by increasing WHC and redness values and by decreasing shear force values.

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DISCLOSURES

The authors declare that they have no competing interests.

SUPPLEMENTARY DATA

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.psj.2020.11.044.

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